

A SUBMILLIMETER HCN LASER IN IRC+10216Peter Schilke¹, David M. Mehringer^{2,3}, & Karl M. Menten¹**ABSTRACT**

We report the detection of a strong submillimeter wavelength HCN laser line at a frequency near 805 GHz toward the carbon star IRC+10216. This line, the $J=9-8$ rotational transition within the (04^0_0) vibrationally excited state, is one of a series of HCN laser lines that were first detected in the laboratory in the early days of laser spectroscopy. Since its lower energy level is 4200 K above the ground state, the laser emission must arise from the inner part of IRC+10216's circumstellar envelope. To better characterize this environment, we observed other, thermally emitting, vibrationally excited HCN lines and find that they, like the laser line, arise in a region of temperature ≈ 1000 K that is located within the dust formation radius; this conclusion is supported by the linewidth of the laser. The (04^0_0) , $J=9-8$ laser might be chemically pumped and may be the only known laser (or maser) that is excited both in the laboratory and in space by a similar mechanism.

Subject headings: circumstellar matter — masers — stars: AGB and post-AGB
— stars: mass loss

1. Introduction

Rotational lines from vibrationally excited states of various molecules are useful probes of the hottest and densest regions of circumstellar envelopes around asymptotic giant branch (AGB) stars. For example, intense maser emission from vibrationally excited SiO

¹Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, Bonn, D-53121, Germany

²California Institute of Technology, MS 320-47, Pasadena, CA 91125

³Present address: University of Illinois, Department of Astronomy, 1002 W. Green St., Urbana, IL 61801

(up to the $v = 4$ state; Cernicharo, Bujarrabal, & Santarén 1993) and H_2O (in the ν_2 bending mode; Menten & Young 1995) is a ubiquitous phenomenon in oxygen-rich red giants and supergiants. Interferometric observations show that these masers arise from a region of thickness a few stellar radii that is located between the photosphere and the inner edge of the dust formation zone (Diamond et al. 1994; Greenhill et al. 1995; see Habing 1996 for a recent review).

In carbon-rich AGB stars, (sub)millimeter-wavelength vibrationally excited rotational lines have been observed from, among others, the HCN, CS, and SiS molecules in particular toward the extreme carbon star IRC+10216 (CW Leo) (Turner 1987a,b; Ziurys & Turner 1986). This object is due to its proximity ($D \approx 140$ pc) and high mass-loss rate ($\dot{M} \approx 2 \times 10^{-5} M_\odot \text{ yr}^{-1}$, Crosas & Menten 1997; Groenewegen, van der Veen, & Matthews 1998) one of the most prolific and best-studied molecular line sources in the sky (see, e.g., Avery et al. 1992; Groesbeck, Phillips, & Blake 1994; Kawaguchi et al. 1995; Cernicharo, Guélin, & Kahane 1999). Recent millimeter-wavelength interferometric observations have shown that the vibrationally excited emission from all three of the molecules mentioned above arises from the innermost parts of IRC+10216’s circumstellar envelope, i.e. from a region with a radius of ≈ 5 –10 stellar radii, r_\star (Lucas & Guilloteau 1992; Lucas & Guélin 1999); we assume a value of $0''.023$ for r_\star (Danchi et al. 1994). Therefore, vibrationally excited lines are interesting probes of the hot ($T \sim 1000$ K), dense regions in which dust grains form (see, e.g., Winters, Dominik, & Sedlmayr 1994; Danchi et al. 1994; Groenewegen 1997).

In the past, only two molecular lines, both from HCN, have been found to show strong maser emission in carbon stars. One of these, the 177 GHz $J=2$ –1 transition from the (01^1_0) excited bending mode was detected toward IRC+10216 by Lucas & Cernicharo (1989). The high flux density (≈ 400 Jy), asymmetric line profile, and time variability (Cernicharo et al. 1999) clearly prove that this line is masing. In this Letter, we report the detection of submillimeter laser⁴ emission in the $J=9$ –8 rotational line within the highly excited (04^0_0) vibrational state of HCN at a frequency near 805 GHz.

⁴In the laboratory spectroscopy literature, the term laser is used for stimulated emission in the far-infrared and submillimeter regimes, i.e. between microwave and optical wavelengths, in particular for the HCN line discussed here. We have followed this convention (see also Strelitski et al. 1996), instead of using the term maser, which is common in radio astronomy.

2. Observations

The observations were made in 1998 February as part of a systematic study of IRC+10216's submillimeter spectrum with the 810 GHz receiver (Kooi et al. 1998) of the Caltech Submillimeter Observatory (CSO) 10.4 m telescope on Mauna Kea, Hawaii. Typical single sideband system temperatures were about 5000 K under excellent weather conditions, i.e. time periods when the precipitable water vapor content was below 1 mm. Pointing was checked by observing the CO(7–6) line toward IRC+10216 itself, resulting in a pointing accuracy of $\approx 2''$. At 805 GHz the beam width is $9''$ (FWHM) and the main beam efficiency was found to be 0.3 from observations of Mars. The spectrometer and observing procedure are described in Menten & Young (1995). We estimate our absolute calibration uncertainties to be $\approx 30\%$. Additional observations of HCN $J=3-2$, $4-3$, and $8-7$ rotational lines within different vibrational states at frequencies near 266, 355, and 709 GHz were made in 1998 April with the same telescope.

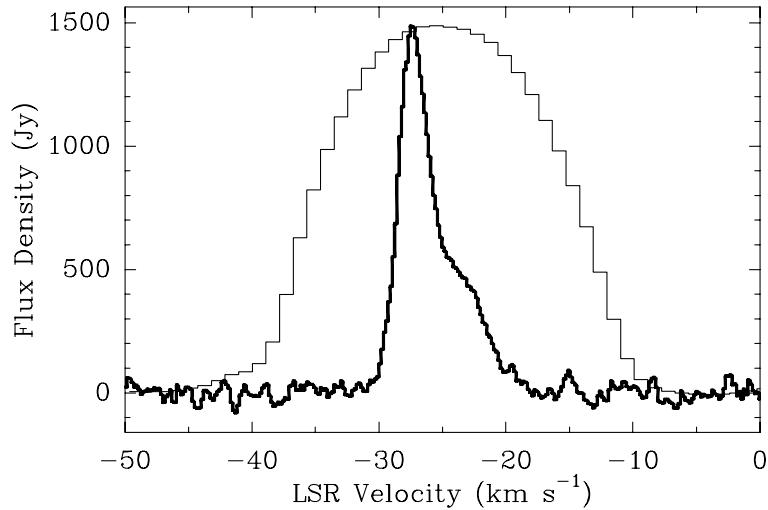


Fig. 1.— Spectrum of the (04^0_0) , $J=9-8$ laser line is shown as the bold line. The very narrow linewidth and asymmetric shape are conspicuous when compared to a spectrum of the HCN $J=4-3$ transition from the vibrational ground state, which is overlaid as the thin line. The flux density scale is appropriate for the (04^0_0) , $J=9-8$ line only.

3. Results and Discussion

3.1. A HCN submillimeter laser

At millimeter wavelengths IRC+10216 has a rich molecular spectrum with emission from more than 50 species arising from a compact central region and/or from hollow shells centered on the star. Radii and thicknesses of these shells depend on the excitation requirements of the molecule in question and on the chemistry. Generally speaking, since submillimeter transitions need much higher densities and temperatures for their excitation than lower frequency lines, the submillimeter spectrum of IRC+10216 is considerably sparser than its millimeter spectrum. In particular, lines from long chain molecules and other radicals, which reside in shells of modest temperature and density (see, e.g., Lucas & Guélin 1999), are largely absent and most of the detected lines can be assigned to simple diatomic or triatomic species emitted from the inner envelope. Moreover, almost all of the submillimeter lines observed toward IRC+10216 are readily assigned to known carriers (Groesbeck et al. 1994), whereas in the mm-range many (weak) lines remain unidentified (Cernicharo et al. 1999).

We were thus surprised to discover a strong spectral line at a frequency of ≈ 804.751 GHz (Fig. 1), which we could not readily identify in available line catalogs (e.g., Pickett et. al. 1998). The line’s frequency was verified by checking its sideband assignment by shifting the local oscillator frequency. With a total width $\lesssim 10 \text{ km s}^{-1}$ (FWZP) the emission covers a much smaller velocity interval than most lines observed toward IRC+10216, which have full widths of 29 km s^{-1} , i.e. twice the terminal outflow velocity, v_∞ . This indicates that the emission arises from a region in which the outflow has not yet reached its terminal velocity and/or that the line shows laser action. The latter is also suggested by the asymmetric line profile which is distinctly different from the symmetric parabolic, rectangular, or double “horn”-shaped profiles expected and commonly observed in the IRC+10216 envelope.

A literature search resulted in the identification of the line with the $J=9-8$ transition of HCN within the $\nu_2 = 4$ vibrationally excited bending mode⁵ (04^0_0), whose lower ($J=8$) level is 4163 K above the ground state and whose frequency was measured by Hocker & Javan (1967) as 804.7509 GHz with an estimated uncertainty of 1 MHz. Most interestingly,

⁵The linear triatomic HCN molecule has three vibrational states, one bending mode ν_2 , with $\nu_2 = 1$ being ≈ 1000 K above ground, and two stretching vibrations: ν_1 , corresponding to the CN stretch, where $\nu_1 = 1$ is 3000 K above the ground state, and ν_3 , the CH stretch, with $\nu_3 = 1$ being 4700 K above ground. [We follow the notation of Herzberg (1945) and note that various papers differ in their usage of the ν_1 , ν_2 , and ν_3 quantum numbers.] The bending mode ν_2 is doubly degenerate; for $\nu_2 \neq 0$ this degeneracy is lifted and the levels are split by rotation-vibration interaction. A new quantum number, ℓ (where $\ell = \nu, \nu - 2, \dots - \nu$) is needed to describe the system. Overtones and combination bands also exist. From here on, the notation $(\nu_1\nu_2^\ell\nu_3)$ is used.

this line was among the first submillimeter laser transitions detected in the laboratory (Mathias, Crocker, & Wills 1965) and is part of the extensively studied $(11^10)/(04^00)$ coriolis-perturbed system around the $J=9$ to 11 rotational levels in these states (Gebbie, Stone, & Findlay 1964; Lide & Maki 1967). These lasers, which are produced in gas discharges, were intensely studied in the early years of molecular laser research (for reviews see, e.g., Chantry 1971; Kneubühl & Sturzenegger 1980; Pichamuthu 1983).

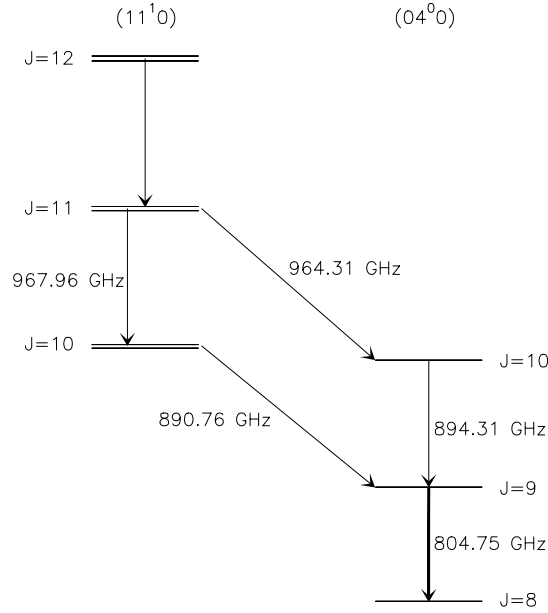


Fig. 2.— Excerpt from the level diagrams of the (11^10) and (04^00) vibrationally excited states of HCN near the Coriolis resonance involving the $J=8$ to 12 rotational levels. Prominent laser lines detected in the laboratory are indicated by arrows along with their frequencies. The bold arrow indicates the (04^00) , $J=9-8$ transition discussed in the present paper.

Fig. 2 shows HCN energy levels around the $J=10$ and $J=9$ rotational states within the (11^10) and (04^00) vibrational ladders. Fortuitously, several of the rotational levels in the (11^10) state are very close in energy to levels with identical J in the (04^00) state. This results in rotation-vibration interactions, i.e. Coriolis coupling, and non-vanishing transition probabilities for cross-ladder transitions (Lide & Maki 1967).

To understand the occurrence of laser action in these cross-ladder and connected transitions, we note that the (100) state is, practically speaking, metastable (Herzberg

1945), with vibrational transitions from the (100) to the (000) ground state being $\sim 2 - 3$ orders of magnitudes slower than (010)–(000) and (001)–(000) transitions (Kim & King 1979). In the laboratory, HCN molecules produced in a gas discharge are distributed over the various vibrational states, most of which [including the (04⁰0) state] will depopulate quickly by spontaneous emission directly to the ground state or by cascading down the vibrational ladder. However, the metastable (100) state, and all combination states building upon it, such as the (11¹0) state, will become overpopulated relative to other vibrational states, including the (04⁰0) state. A consequence of this is laser action in the $J=11-10$ and $10-9$ cross-ladder transitions, which in turn causes the (04⁰0), $J=10$ and $J=9$ states to be overpopulated and the (11¹0), $J=11$ and 10 to be underpopulated, resulting in laser action in the (04⁰0), $J=10-9$ and $9-8$ as well as in the (11¹0), $J=12-11$ and $11-10$ transitions.

It is interesting to note that of the more than 120 cosmic maser and laser transitions known so far, the HCN (04⁰0), $J=9-8$ line is, apart from the $(J, K) = (3, 3)$ inversion line of ammonia (NH₃, Mangum & Wootten 1994), the only one that has been reported to show maser action in an astronomical object as well as in the laboratory. In the case of the NH₃ (3,3) maser, inversion in the laboratory (Gordon, Zeiger, & Townes 1954) is achieved by completely different means than in interstellar space (Flower, Offer, & Schilke 1990). In contrast, quite remarkably, the HCN laser might be produced in IRC+10216’s circumstellar envelope by essentially the same mechanism as in a gas discharge cell. This will be discussed in §3.3 after we have described the environment in which the laser arises.

3.2. Vibrationally excited HCN in IRC+10216’s innermost envelope

Since the (04⁰0), $J=9-8$ line is emitted from a very highly excited vibrational state of the molecule, we try to characterize the excitation conditions of hot HCN in IRC+10216’s inner envelope by using our own multi-line observations as well as data from the literature.

The first observations of vibrationally excited HCN in IRC+10216 were made by Ziurys & Turner (1986), who detected the $J=3-2$ transition in the (01^{1c}0), (01^{1d}0), and (02⁰0) states and find the levels to be thermally populated. Guilloteau, Omont, & Lucas (1987) report strong maser emission in the (02⁰0), $J=1-0$ transition toward the carbon star CIT 6. Weaker maser emission in this line is found toward other carbon-rich stars (Lucas, Guilloteau, & Omont 1988) including IRC+10216 (Guilloteau et al. 1987). Interferometric observations toward the latter star suggest that the maser action arises from within a region of radius $0''.25$, or $\approx 10 r_*$ (Lucas & Guilloteau 1992). Strong maser action in the (01^{1c}0), $J=2-1$ transition was found toward IRC+10216 by Lucas & Cernicharo (1989), who also observed thermally excited lines from the (01^{1d}0), (02⁰0) and (02²0) states.

Rotational lines from the (100) and (001) states of HCN were first detected by Groesbeck, Phillips, & Blake (1994), who observed the $J=4-3$ transition in these as well as in several of the $(01^{\ell}0)$ and $(02^{\ell}0)$ states. Using the Infrared Space Observatory (ISO) Cernicharo et al. (1996) found emission in these vibrational states from the $J=18-17$ up to the $J=48-47$ rotational lines. These observations indicate a vibrational temperature of 1000 K.

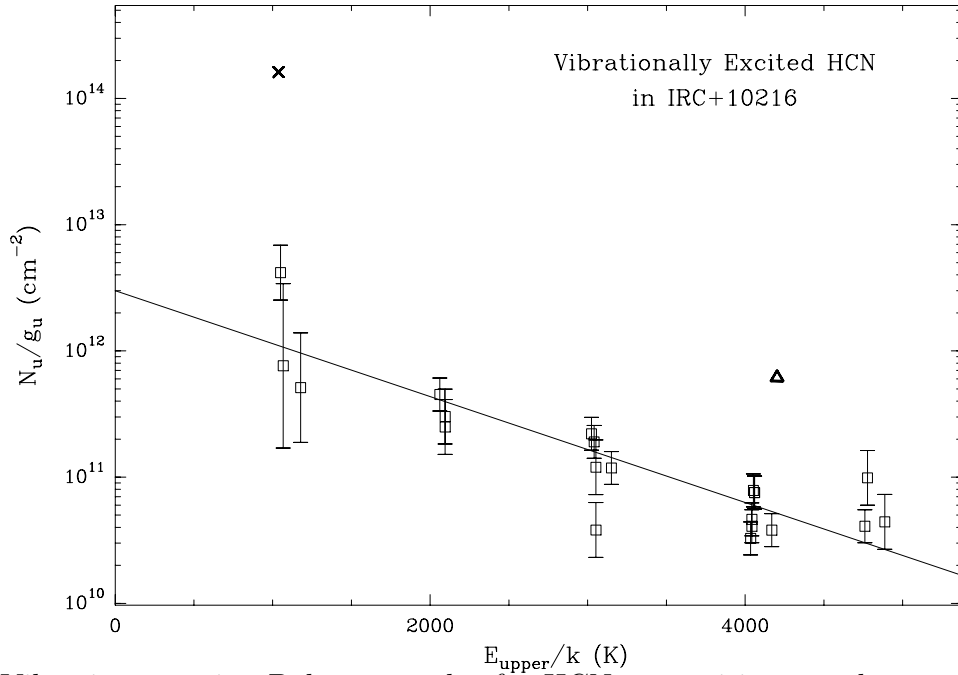


Fig. 3.— Vibration–rotation Boltzmann plot for HCN, comprising our data and the (020) data from Groesbeck et al. 1994. The entries for the (01^1c0) maser and (04^00) laser lines are marked as an “x” and a triangle, respectively, and are not used in the fit.

We complemented the data from the literature by using the CSO to observe various other thermally excited lines from vibrationally excited states with energies comparable to or even exceeding that of the (04^00) , $J=9-8$ line. Details of these observations will be given in a future publication. Using the complete set of data we construct the vibrational-rotational excitation diagram shown in Fig. 3, for which we assume a point-like source and “normalize” the intensities, which were measured with different resolutions, to a $11''$ FWHM beam. Clearly, the abscissa values of the data points representing the (01^1c0) , $J=2-1$ maser and our (04^00) , $J=9-8$ laser are much higher than the thermal equilibrium values expected for these lines. Excluding those points, a least square fit yields a vibrational temperature of 1000 K, similar to the value found by Cernicharo et al. (1996). Assuming that the brightness temperature of the thermally excited lines in the (04^00) state is equal

to or smaller than this number, we find an lower limit of $0''.08$, or $\approx 3.5 r_*$ for the radius of the emitting region. This is comparable to the upper limit found interferometrically for the radius of the (02^00) , $J=1-0$ emission region and is close to the dust condensation radius, which according to the model calculations of Groenewegen (1997) is at $4.5 r_*$ at a temperature of 1075 K. The high excitation vibrationally excited thermal lines have, in contrast to the laser line, symmetric profiles covering a velocity range that is very similar to that of the laser line, i.e. much narrower than that of lines from the vibrational ground state. We therefore conclude that the HCN laser line is formed at the dust condensation radius at a temperature of 1000 K.

Both the laser discussed here and the (01^1_0) , $J=2-1$ and (02^0_0) , $J=1-0$ masers exhibit enhanced emission at velocities that are blueshifted relative to the stellar velocity. If a systematic outflow has already started in the part of the envelope giving rise to the HCN masers, one would expect the blueshifted emission to arise from between the star and the observer, allowing for the possibility that its greater intensity is due to amplification of background emission from the stellar photosphere. A significant reduction of the redshifted emission due to geometrical blocking by the star can be excluded if the size of the HCN emission region has dimensions of the order discussed above. On the other hand, we know from Very Long Baseline Interferometry of SiO masers in O-rich Mira stars that red- and blue-shifted SiO maser emission does not necessarily arise from, respectively, the back and front parts of the circumstellar shell; instead ring-like emission distributions are observed, indicating tangential amplification (Diamond et al. 1994). Recent high resolution infrared observations in the K' band (Weigelt et al. 1998) indicate that the dust shell of IRC+10216 is extremely clumpy and asymmetric to a radius of $\approx 0''.2$ or $9 r_*$, which is comparable to the size of the dust formation and HCN laser/maser region. Maser pumping by such a highly anisotropic infrared field would certainly result in an inhomogenous emission distribution giving rise to an asymmetric line profile. Very high resolution interferometric observations with future instruments such as the Atacama Large Millimeter Array (ALMA) are needed to image the maser emission and study its dynamics.

3.3. Pumping Schemes

A direct radiative pump from the ground state into the (11^1_0) state does not seem likely, since in that case the other vibrational states would be preferentially populated by virtue of their higher transition probabilities. We were unable to check for possible line overlaps between infrared transitions from HCN and other molecules abundant in IRC+10216, such as CO, and pumping by that mechanism remains viable in principle.

Collisional pumping might also be possible, since the critical density (i.e., the ratio of the Einstein A-coefficient to the collisional excitation coefficient) of the (100) stack, which includes, among others, the (11¹0) combination state, is lower than that of the other vibrational states, if we assume comparable collision rates. A more detailed analysis of this mechanism requires knowledge of collisional excitation coefficients.

Most interestingly, chemical pumping, which has been invoked to explain the laboratory HCN lasers (see, e.g., Chantry 1971; Pichamuthu 1983), might also be at work in IRC+10216. The basic idea is that the HCN molecules are formed in random vibrational states, and a population inversion is achieved in the (11¹0)/(04⁰0) system because of the wide difference in the radiative decay rates of the different vibrational levels. For this mechanism to work, the number of HCN creation events per time unit should exceed the number of HCN laser photons emitted by a considerable amount. HCN is formed in thermochemical equilibrium (see Tsuji 1964), where the reaction of CN with H₂ is likely to be a major channel. In the following we assume that HCN formation proceeds at a typical rate of 10^{-10} s^{-1} in a shell between radii of 2×10^{14} and 3×10^{14} cm, i.e. just interior to the dust formation radius. If we further assume a CN abundance of 10^{-11} (the value at 1000 K; Lafont, Lucas & Omont 1982) and an H₂ density of 10^{12} cm^{-3} , we calculate 8×10^{45} HCN creation events per second. From our spectrum we determine an integrated line flux of $6100 \text{ Jy km s}^{-1}$, which corresponds to an isotropic photon luminosity of $7 \times 10^{43} \text{ s}^{-1}$. Given that any alternative production mechanism would only increase the number of creation events, it appears that chemical pumping seems possible, although the uncertainties in the numbers used are considerable.

Finally, we note that if the circumstellar 805 GHz laser results from overpopulation of the (11¹0) state and (11¹0)–(04⁰0) cross-ladder transitions, as is highly likely, one would also expect the other transitions of this Coriolis-coupled system, like in the laboratory, to show strong laser action toward IRC+10216. Of these (see Fig. 2), the (11¹0)–(04⁰0), $J=10-9$ cross ladder transition at 890.76 GHz and the 894.31 GHz $J=10-9$ line within the (04⁰0) state are, in principle, observable from high, dry mountain sites, but outside the frequency range of the receiving system currently available to us. The (11¹0)–(04⁰0), $J=11-10$ and (11¹0), $J=11-10$ transitions at 964.31 and 967.96 GHz, respectively, should be observable with the Stratospheric Observatory for Infrared Astronomy (SOFIA).

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